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THE ROCKET INTERFEROMETER TRACKING (RIT) SYSTEM

by Michael Spafford, Richard Wiack, and Ronald Woodman

Goddard Space Flight Center
Greenbelt, Md.

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SUMMARY

A Rocket Interferometer Tracking (RIT) system is described. It uses a modified 108 Mc Minitrack receiver converted for 73.6 Mc operation and a newly developed phase measuring system. The output of the system is real time direction cosine data for two channels, East-West and North-South, in analog and digital form. The analog data are recorded on an x-y recorder and on a strip chart recorder; and the digital data are automatically recorded on punched tape. The RIT system has been integrated with the ranging portion of the Radio Doppler Interferometer Tracking system (RADINT) at the Wallops Island Launch facility, and records the range data on the same punched tape.

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INTRODUCTION

The interferometer method is a simple and accurate technique for radio tracking of rockets and satellites. Several systems based on this technique have been developed and are in actual use; among others, the Radio Doppler Interferometer Tracking System (RADINT)† for sounding rockets and the Minitrack tracking system for satellites. There has been one drawback with the interferometer technique as compared to other tracking systems using radar or automatic tracking antennas: because of an inherent ambiguity problem, there is no real time information. Manual or computer processing is necessary, with consequent delay in availability of the tracking data.

The Rocket Interferometer Tracking (RIT) system, by using a different phase measuring technique, circumvents this limitation. It is a real time system; real time direction cosine data are obtained, recorded, and displayed. Ambiguity of the interferometer data is resolved by "tracking" the rocket from its known launching position. After the rocket is launched the RIT system automatically keeps track of the correct interferometer lobe. The phase measuring technique used permits a relatively narrow post-detection bandwidth, thereby avoiding the need for computer data smoothing.

The RIT system, as do other interferometer systems, obtains the angular position of a radio signal source by measuring the phase difference of signals arriving at two pairs of antennas, one in the North-South and the other in the East-West direction. The antennas in each pair are spaced 16 wavelengths apart. These phase differences are related to the directional cosine of the source by the following relations:

$$\phi_{E-W} = 16 \cos \alpha , \quad (1)$$

$$\phi_{N-S} = 16 \cos \beta , \quad (2)$$

*Mr. Woodman is an employee of the Instituto Geofisico del Peru, Lima, Peru.
†The RADINT system was formerly known as the Single-Station Doppler (SSD) tracking system.

where

ϕ_{E-W} = phase difference in wavelengths for the East-West antenna pair,

ϕ_{N-S} = phase difference in wavelengths for the North-South antenna pair,

$\cos\alpha$ = direction cosine of the source with respect to the East-West antenna baseline, and

$\cos\beta$ = direction cosine of the source with respect to the North-South antenna baseline.

The RIT system measures this phase difference in fractional wavelengths as well as the number of whole wavelengths, without ambiguity, in both analog and digital form. The analog direction cosine data are recorded and displayed on an x-y type recorder and also on a strip chart recorder. The graph paper used with the x-y recorder converts the data into azimuth-elevation form, which is a more convenient form of real time data. The strip chart recorder records the analog data as direction cosine data together with time.

Range from a RADINT system, time, and the direction cosine data from the RIT system are all recorded digitally on punched tape. The station is equipped with a Flexowriter and the experimenter can have the position information in tabulated form within a half-hour after the tracking operation is completed.

The RIT type of tracking system potentially has two other advantages. First, the real time analog direction cosine data could be used to position a telemetry antenna automatically. A model x-y type mount, automatically driven by such data, has been developed at Goddard Space Flight Center. Second, the analog directional cosine data together with the range data could be used to compute the real time altitude and the sub-rocket position (x, y) coordinates. These could be displayed for range safety purposes or recorded for the experimenter.

SYSTEM DESCRIPTION

The RIT system (Figure 1) consists of an antenna portion, an R.F. receiver portion, a servo phase measuring unit, an x-y plotter, a centralized control panel, and a digital portion. The RIT system tracks a 73.6 Mc beacon.

Antenna System

The RIT system makes use of four crossed-dipole antennas, each spaced 1/4 wavelength over a ground screen, and accurately positioned 16 wavelengths apart. Two of these antennas comprise the North-South baseline and two the East-West baseline (Reference 1).

Receiver System

It was decided to use an interferometer receiver of the Minitrack type since it has proved to be a well designed, reliable, accurate and stable receiver with six years of field operational use in tracking satellites. There were two alternatives: either build a new Minitrack type receiver for 73.6 Mc, the beacon frequency assigned for rocket tracking purposes, or modify the

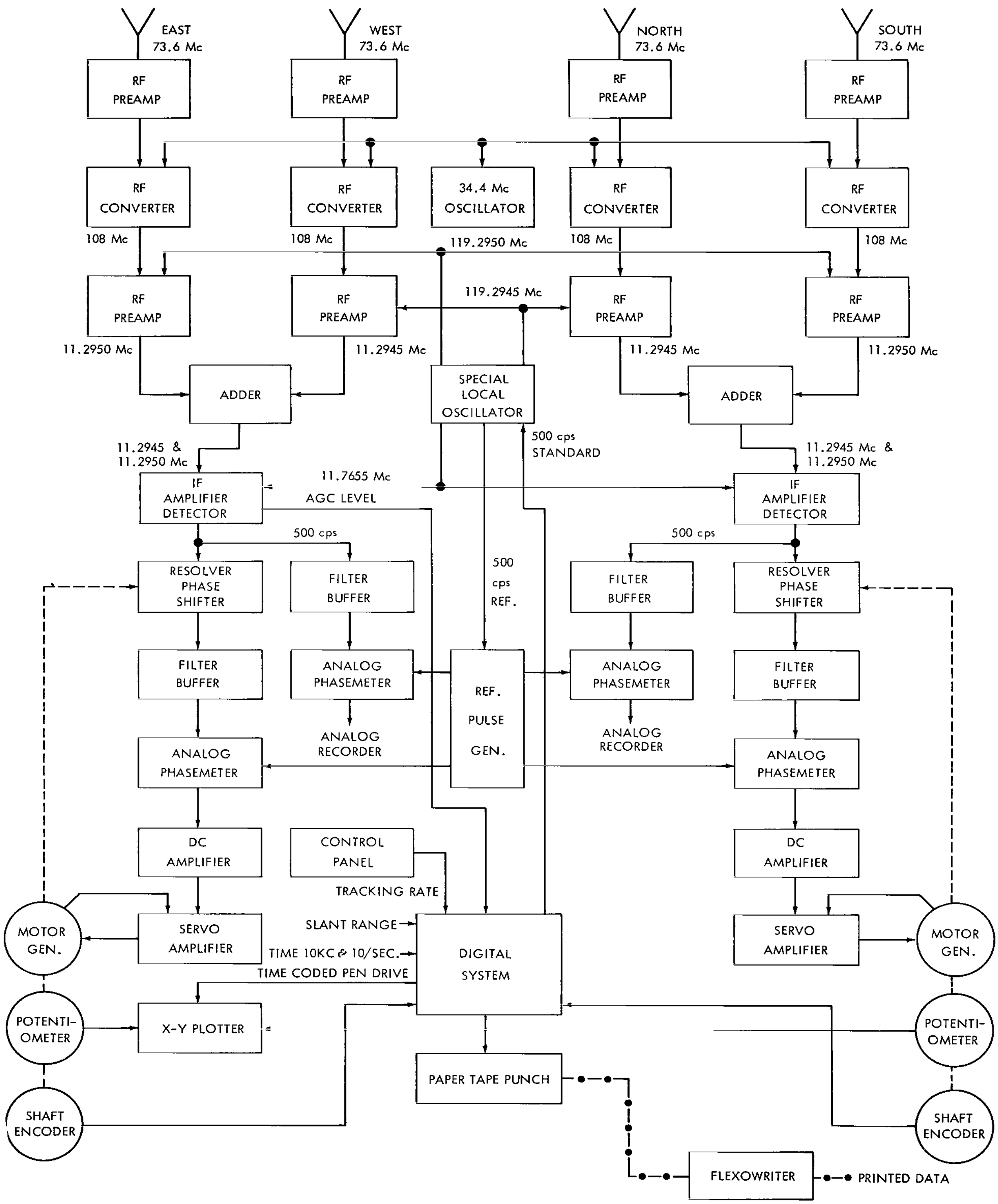


Figure 1—The Rocket Interferometer Tracking (RIT) system.

existing 108 Mc Minitrack receivers for 73.6 Mc operation. The second course was chosen because several 108 Mc receivers were available and the construction of RF up-converters for these receivers was easily done. If more RIT systems were to be built, the first alternative would have been technically more desirable.

Figure 2 shows a block diagram of one receiver channel (the North-South channel). The existing 73.6 Mc preamplifiers of the RADINT system are used; the output is then converted to 108 Mc and fed to the Minitrack receivers.

The 73.6 to 108 Mc up-converter (Figure 3) consists of four balanced crystal mixers, one for each antenna signal and all fed by a common 34.4 Mc local oscillator. Crosstalk between channels is kept to a minimum by isolating the common 34.4 Mc L.O. signal through hybrid dividers.

Since the 108 Mc Minitrack receiver has been described in great detail elsewhere (References 2, 3), a brief description will suffice here. The signals received by each interferometer antenna pair are amplified by two low noise preamplifiers and converted to two different first IF frequencies. The latter differ from each other by exactly 500 cps plus a phase difference equal to the phase difference between the antenna inputs; this is the phase difference that is to be measured. The 500 cps difference is obtained by using two different first L.O. frequencies servo controlled to be exactly 500 cps apart. This is a typical Minitrack technique which allows use of one common IF amplifier with a relatively narrow bandwidth for both signals. Any shift in the

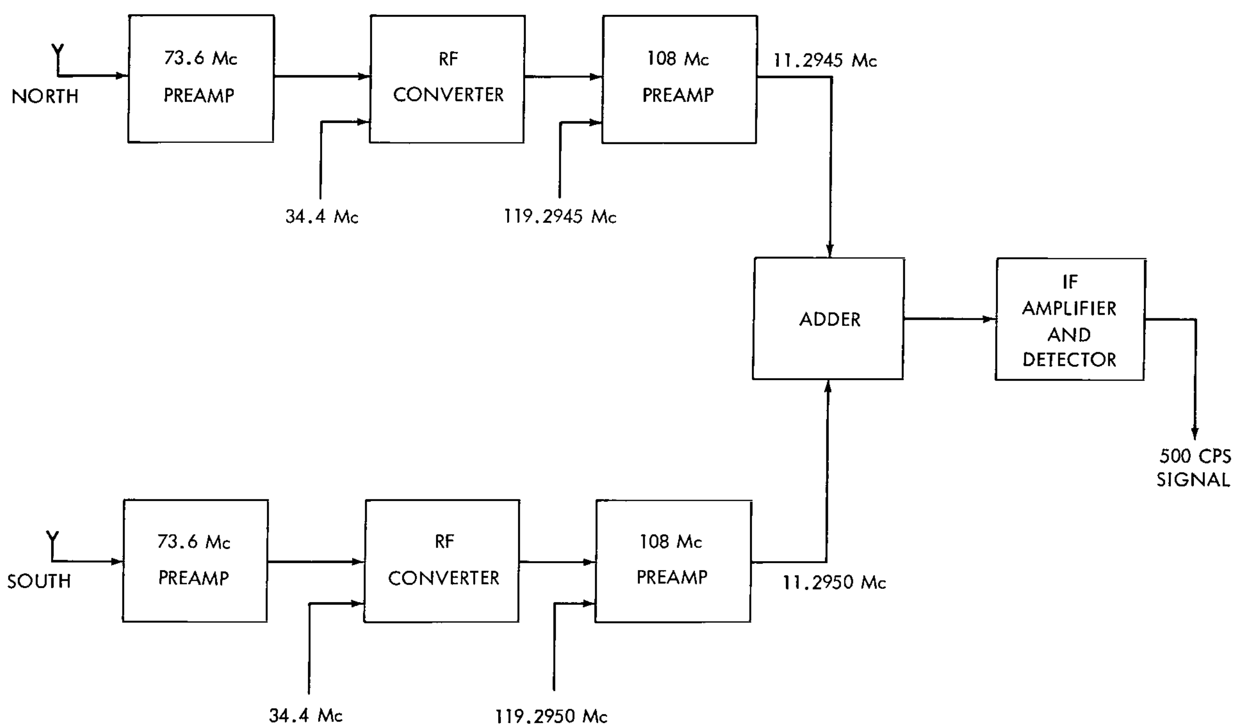


Figure 2–RF signal flow diagram–one channel only.

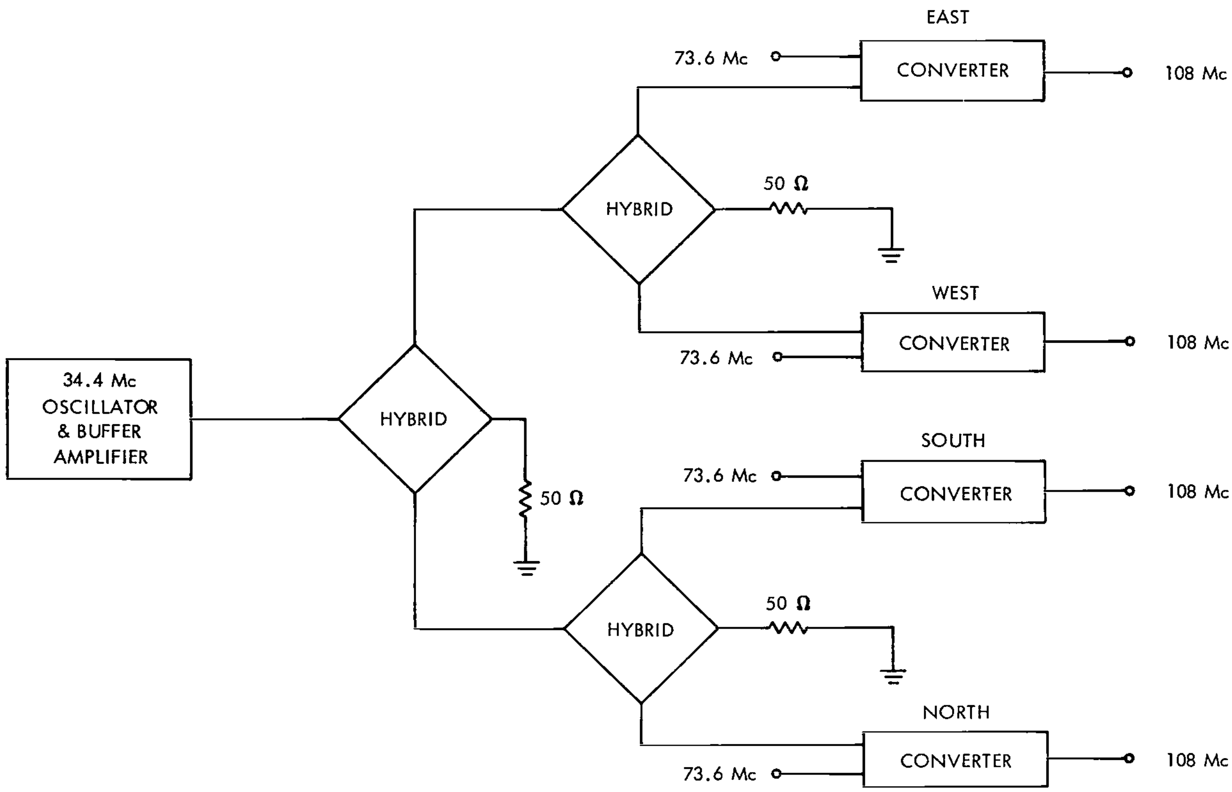


Figure 3—RF up-converter, 73.6 to 108 Mc.

phase characteristics of the IF amplifier itself affects both signals identically, thereby reducing their relative phase shift to a minimum. There is a second conversion in the IF amplifier to 470.0 kc and 470.5 kc, and most of the receiver amplification is done at these frequencies. The pre-detection bandwidth is 12 kc. The two-frequency output (470 kc and 470.5 kc) is fed to a detector which detects the beat between these two frequencies, i.e., a 500 cps signal with a phase relative to a 500 cps reference signal which is identical to the phase difference between the two interferometer antennas.

Servo Phasemeter

The function of the servo phasemeter is to measure the phase of the 500 cps signal from the receiver detector as compared to the phase of the 500 cps reference, and to calculate the direction cosine (see Equations 1, 2).

Most conventional phasemeters, including the original Minitrack phasemeter, convert phase into voltage or into a digital number in such a way that this voltage or digital number repeats itself periodically every 2π radians. The functional relationship between phase and time is therefore a discontinuous one. The disadvantage of this approach is that linear filtering of the output is not possible and that there is an ambiguity problem in determining the integral number of phase cycles (or lobes) corresponding to the integral number of whole wavelengths in ϕ.

The phasemeter used in the RIT system converts the phase of the 500 cps signal into a shaft rotation. The advantage of this type of transformation is that it is continuous. As the phase of the signal increases, the shaft angle increases continuously and monotonically. As the phase goes through one cycle and starts a new one, the shaft goes through one revolution and begins another. This technique permits linear filtering; very narrow bandwidths can also be obtained.

The shaft position is a measure of the fractional as well as the integral number of phase cycles in terms of a fraction of a revolution and number of revolutions respectively. This shaft position is determined by means of a potentiometer for an analog output, or by a shaft encoder for a digital output. The direction cosine corresponding to a particular phase difference is measured directly from the shaft position by proper scaling.

A block diagram of the servo phasemeter is shown in Figure 4. The phase of the 500 cps input signal is converted to angular shaft rotation in the following manner:

The 500 cps input signal is phase shifted by a resolver phase shifter so that the shifted signal is kept in phase with the 500 cps reference. The resolver phase shifter is servo controlled by means of a servomotor. If the shifted signal is not in phase with the reference, an error

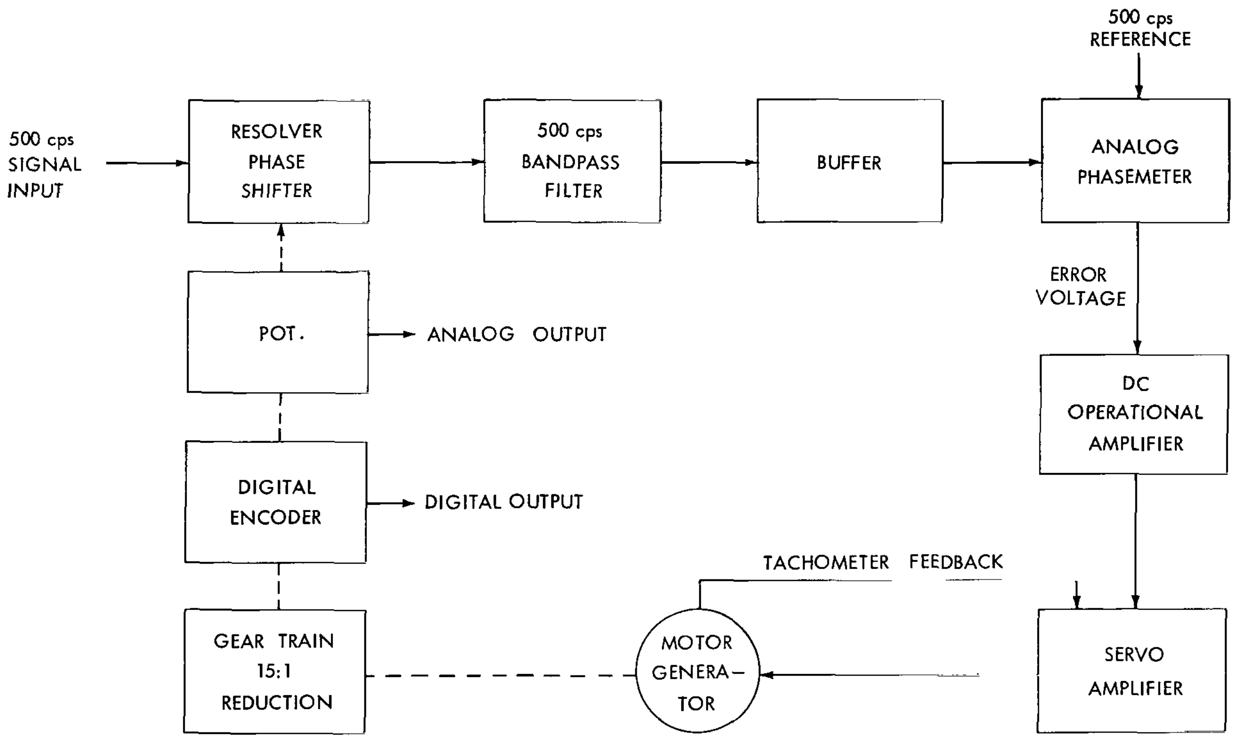


Figure 4—Servo phasemeter—one channel only.

voltage is generated by the analog phasemeter, amplified by the dc operational amplifier, converted to ac by means of a modulator, and fed to the servo amplifier of a speed controlled motor-generator. The motor, through proper speed reduction, then drives the shaft of the resolver phase-shifter rotor, and shifts the phase of the input signal until the error is reduced to zero.

The phase at the output of the resolver phase shifter, ϕ_0, is

$$\phi_0 = \phi_s - \theta \tag{3}$$

where

ϕ_s = phase of the 500 cps input signal, and

θ = angular rotation of the resolver phase-shifter shaft.

Under steady-state conditions (the dynamic behaviour will be seen later), the error of the loop is zero, i.e.,

$$\phi_0 - \phi_r = 0$$

or

$$\phi_0 = \phi_r , \tag{4}$$

where ϕ_r is the phase of the 500 cps reference. And if we take the phase of the 500 cps reference signal as the arbitrary zero, we have

$$\phi_s - \theta = \phi_0 = \phi_r = 0 ,$$

or

$$\theta = \phi_s .$$

That is, the rotor shaft position, θ, of the resolver phase shifter equals the phase of the 500 cps signal, ϕ_s, which in turn equals the phase difference between the interferometer antennas. This phase difference is related to the direction cosine by Equation 1 or 2:

$$\theta = 16 \cos \alpha .$$

Thus, for θ in revolutions,

$$\cos \alpha = \frac{\theta}{16} .$$

The range of the direction cosine data is from -1 to +1, corresponding to -16 to +16 turns, a total range of 32 turns for θ. The analog direction cosine is obtained from a potentiometer, referred to as the 1x potentiometer, located on the gear train with a step down gear ratio of 32:1 from the resolver shaft. B^+ and B^- voltages are connected across the potentiometer such that zero volts corresponds to the center of the potentiometer and to $\cos\alpha = 0$. The output from the East-West channel potentiometer is used to drive the x coordinate of the x-y recorder, and the North-South potentiometer output drives the y coordinate. This analog output is also available for a strip chart recorder and for any real time analog computation. Another potentiometer in each channel is located on a shaft geared down by a 1.6:1 ratio from the resolver and is used for strip chart recording; the resolution of this output is 20 times larger than the former.

The digital direction cosine data are obtained by means of a digital shaft encoder on the gear train. The best location for the encoder would have been on the resolver shaft in order to avoid gear backlash. In practice the encoder has been geared down from the resolver shaft by a 1.6:1 ratio. For one revolution of the *resolver*, the 1000 count/revolution *encoder* counts 625 which corresponds to a change in direction cosine of .0625. The digital encoder is fully described in the digital section.

The accuracy of the servo phasemeter, i.e., the accuracy of the transformation of the input phase signal to digital direction cosine data is determined primarily by the linearity of the resolver phase shifter, and in the RIT system the accuracy is of course 1.6 times better than is required. The resolver phase shifter linearity of 1 part in 10^3 corresponds to a servo phasemeter accuracy of .0000625 direction cosine units or 6 parts in 10^5. The overall accuracy of the RIT system appears to be in the order of 2 parts in 10^4.

The accuracy of the unambiguous analog output is again determined by the linearity of the potentiometer, 1 part in 10^3. The accuracy of the geared up potentiometer is 20 times better but it cannot be used for real time computations since it is discontinuous and therefore ambiguous.

The servo phasemeter not only measures the phase of the signal and computes the direction cosine but also determines the post-detection bandwidth of the system. The servo phasemeter is essentially a tracking filter with all the advantages thereof.

For its dynamic analysis we can consider the phasemeter as a positioning servo wherein the phase of the input signal is the command signal and the resolver shaft the controlled output. There are two modes of operation, one with the 3 cps bandwidth, the other with the 0.3 cps bandwidth. Figures 5 and 6 show the functional block diagram with corresponding transfer functions.

The RIT system has been designed to employ a type II servo system with a minimum transient time for each particular bandwidth. This transient time is the same for either step or ramp input. For a ramp input, i.e., for a constant phase rate input, the steady state error is zero. This is due to the Type II design and is an advantage over conventional passive filters in which the output lags the input by a time equal to approximately the inverse of the bandwidth in radians.

The open loop transfer function for the 3 cps bandwidth is

$$G(s) = \frac{\theta(s)}{\phi_0(s)} = \frac{372(s + 3.71)}{s^2(s + 33.4)},$$

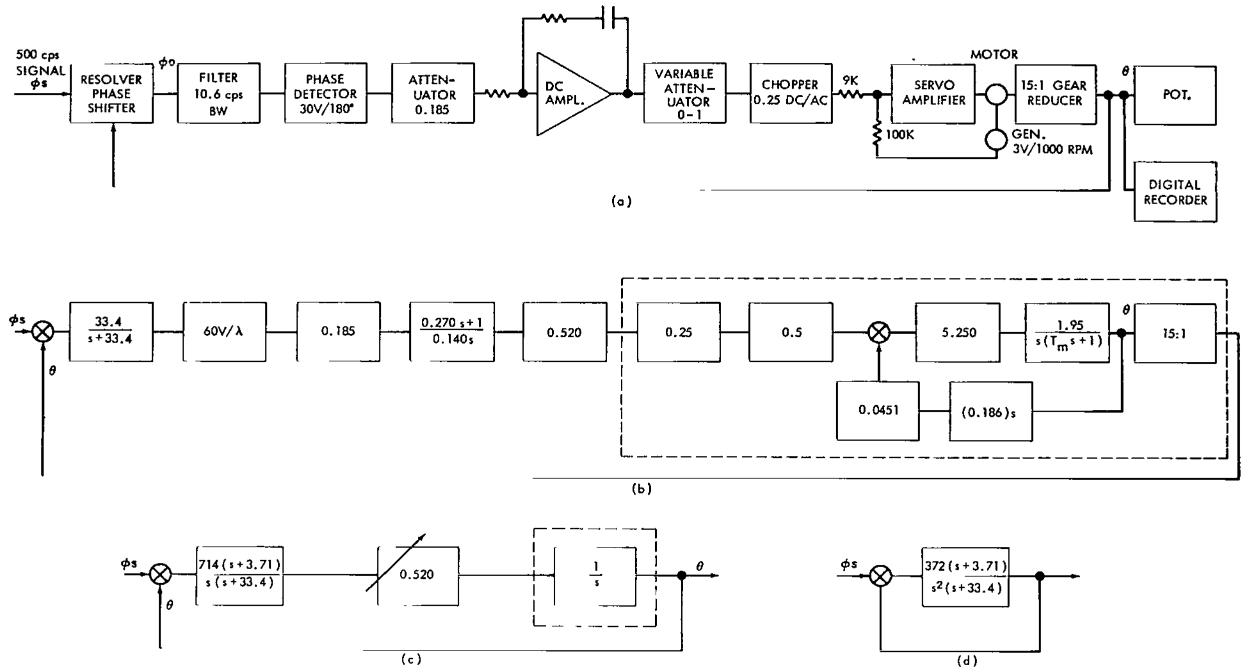


Figure 5—Diagrams of the transfer function for the 3 cps bandwidth servo phasemeter: (a) functional diagram; (b) dynamic diagram showing transfer function of each block; (c) same as (b) but simplified; (d) further simplified.

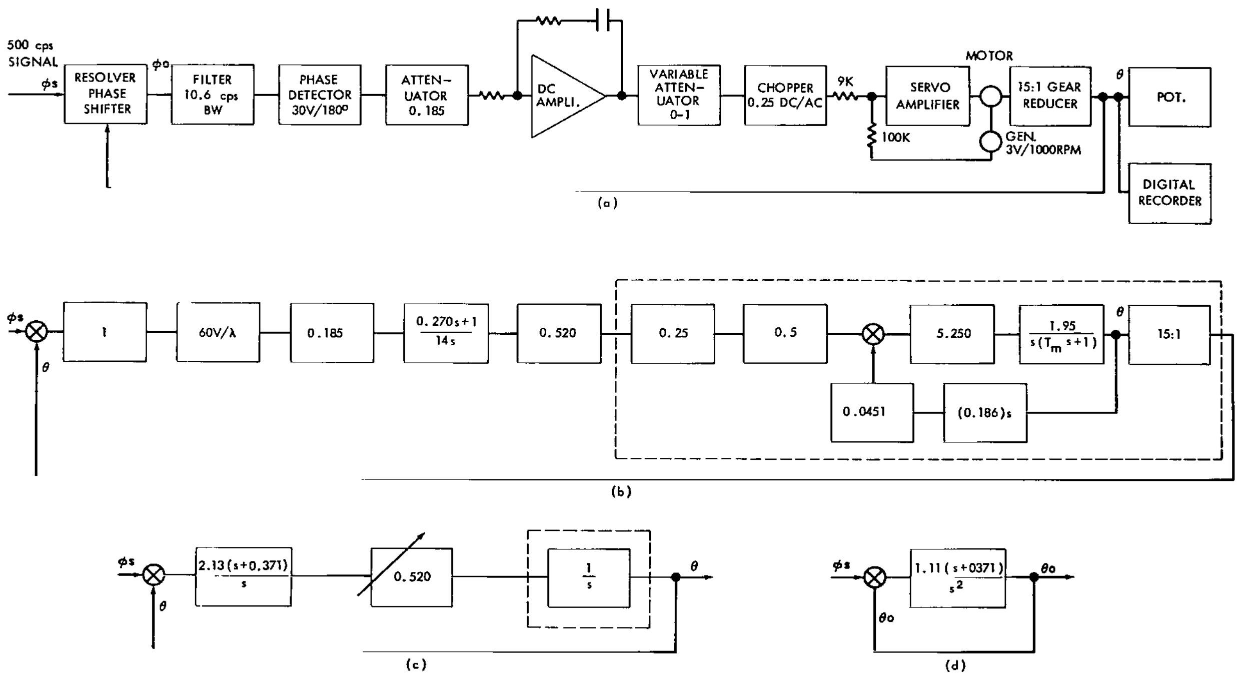


Figure 6—Diagrams of the transfer function for the 0.3 cps bandwidth servo phasemeter: (a) functional diagram; (b) dynamic diagram showing transfer function of each block; (c) same as (b) but simplified; (d) further simplified.

The two integrating poles at the origin are realized by means of a dc operational amplifier integrator and the integrating action of the velocity controlled motor-generator. The stabilizing zero at $s = 3.71$ is realized by placing a resistor in series with the integrating capacitor in the operational amplifier. The pole at $s = 33.4$ (Figure 7) is due to the effect of the 500 cps bandpass filter, located after the resolver phase shifter, on the phase of the 500 cps signal. It is an approximation of the filter's response to phase deviations no larger than $\pi/4$ and assumes that the signal is well represented by taking the two nearest sidebands of a phase modulated signal. The function of this bandpass filter (10.6 cps bandwidth) is to filter out any excessive noise before the phase detector, to reduce heating of the motor caused by high frequency signals, and to improve the linearity of the phase shifter by filtering out any 500 cps harmonics. Its effect on the system's bandwidth is secondary, and in the 0.3 cps bandwidth mode is negligible.

Figure 7 shows a root locus plot for the 3 cps mode as well as the pole and zero configuration for the particular gain selected. The corresponding closed loop transfer function is

$$\frac{\theta(s)}{\phi_s(s)} = \frac{26.1(s + 3.71)}{(s + 11.25)^3}$$

with a frequency response as shown in Figure 8 with a bandwidth of 3 cps to the -3 db point and a 40 db/decade rolloff. Figure 9 shows the time response of the system for a step and a ramp input and the system error, i.e., $\theta - \phi_s$, as a function of time. Note that after transient time of approximately 0.8 second the error is reduced to practically zero in both case.

For an input signal with constantly accelerating phase, the output of the system is in error by

$$\theta - \phi_s = \frac{2a}{K_a}$$

where a is the input acceleration, and

$$K_a = s^2 G(s)\Big|_{s=0} = 41.4 \ ,$$

is the acceleration constant of the system. With the exception of a few seconds after rocket launch, acceleration errors are negligible. During the launch phase, which consists primarily of the first 10 to 20 seconds, tracking accuracy requirements are not stringent and relatively large errors can be permitted provided they are less than half a phase cycle or lobe so that the system does not lose lock. We can observe from the ramp input response (Figure 9) that if the phase rate were to change from zero to 5 cycles per second instantaneously (an infinite acceleration impulse), then the maximum error would be 0.3 of a phase cycle. The actual case is less severe since the phase rate is acquired very gradually. The limiting factor on the system's ability to maintain phase-lock is the maximum phase rate it can track; and this in turn is limited by the maximum speed of the servo motor. The present rate is 4.5 phase cycles per second, a rate that adequately meets the present requirements as used at Wallops Island. It should be noted that as the distance from the launch pad to the antenna system is increased, the maximum phase rate decreases; however, problems associated with obtaining range data increase.

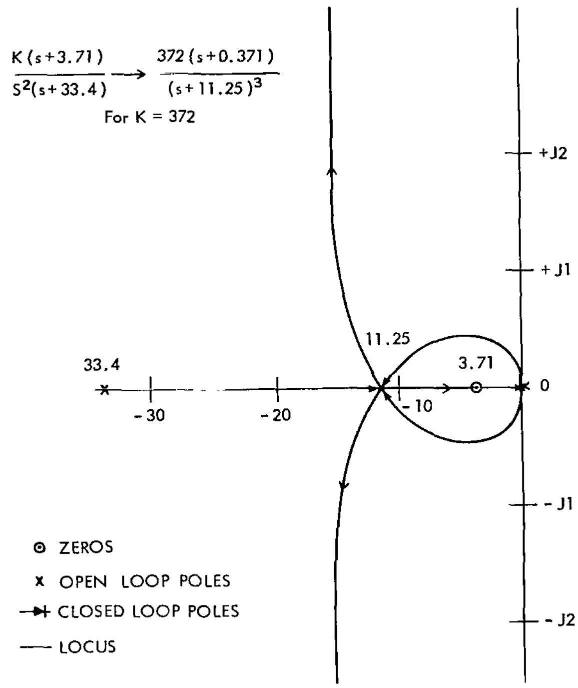


Figure 7—Root locus plot for the 3 cps bandwidth.

The dynamics of the 0.3 cps bandwidth mode is similar to that of the 3 cps bandwidth mode but scaled 10 times slower. The open loop transfer function is similar to that of the 3 cps bandwidth with the stabilizing zero at 1/10 of the 3 cps bandwidth value and with no pole due to the 500 cps bandpass filter. The 500 cps filter is still in the circuit with the same bandwidth and for the same purpose as before but its effects on the system dynamics are at frequencies much higher than the critical ones and can be neglected. The open loop transfer function for the 0.3 cps bandwidth is

$$G(s) = \frac{1.11(s + 0.371)}{s^2} .$$

Figure 10 shows the corresponding root locus plot and the pole and zero configuration of the closed loop for this mode of operation. The corresponding closed loop transfer function is

$$\frac{\theta(s)}{\phi_s(s)} = \frac{1.11(s + 0.371)}{s^2 + 1.11s + 0.412} .$$

The frequency response is shown in Figure 11. The open loop transfer function is realized by simply changing the value of two resistors to lower the frequency of the stabilizing zero and to change the gain of the servo loop by a factor of 10. Since only resistors need be switched to change

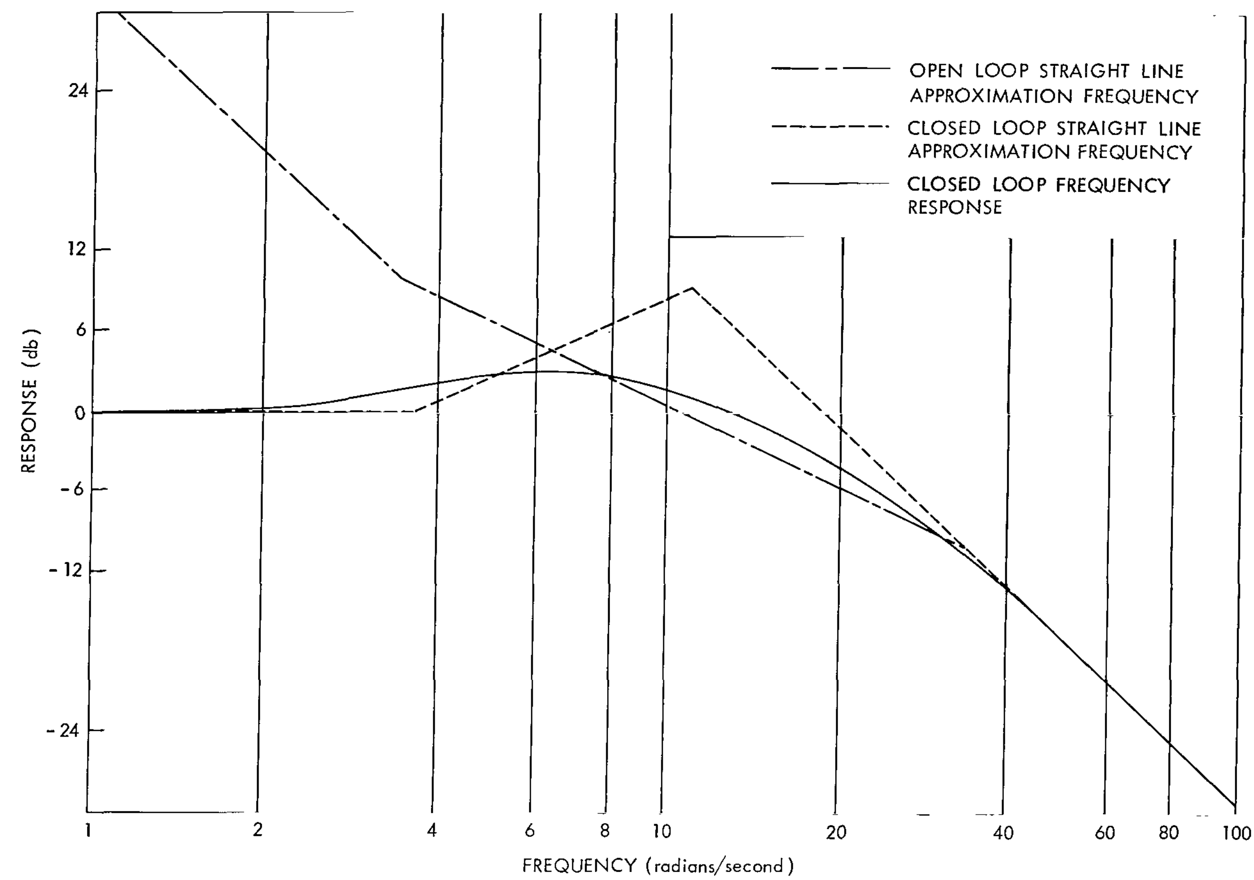


Figure 8—Frequency response for the 3 cps bandwidth.

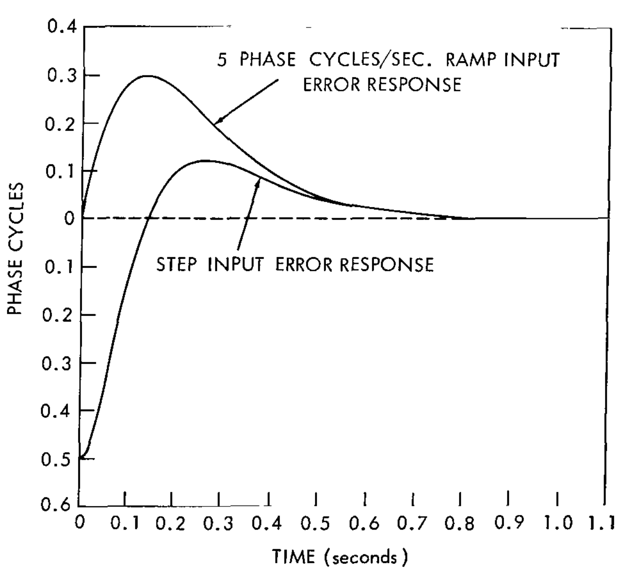


Figure 9—Time response for the 3 cps bandwidth.

from one bandwidth to another, no phase or phase rate transients are introduced into the loop since the phase rate is "memorized" in the integrating capacitor.

The time responses for step and ramp inputs are shown in Figure 12. After approximately 8 seconds, both transient errors are reduced to practically zero. As in the previous mode there is no output lagging error for a constant phase rate input, limited only by the maximum tracking servometer speed.

The acceleration constant, K_a, for this mode is

$$K_a = s^2 G(s) \Big|_{s=0} = 0.418$$

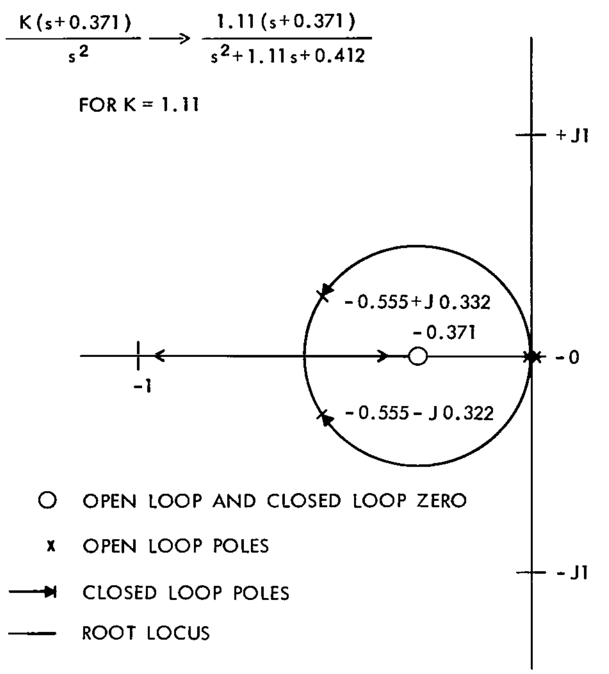


Figure 10–Root locus plot for the 0.3 cps bandwidth.

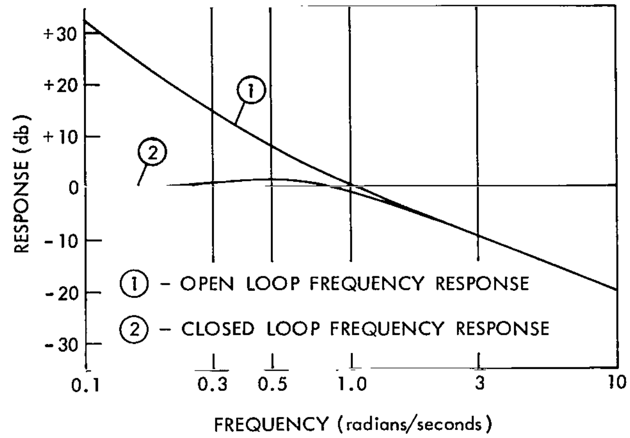


Figure 11–Frequency response for the 0.3 cps bandwidth.

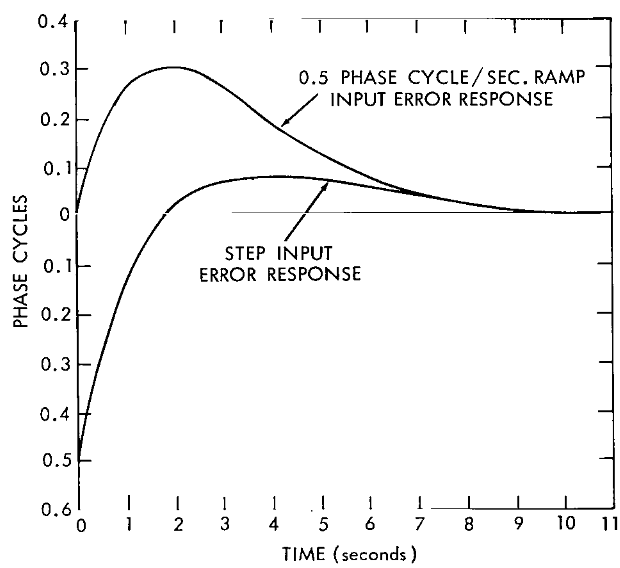


Figure 12–Time response for the 0.3 cps bandwidth.

and the error due to a constant acceleration a is given by

$$\phi_s(t) - \theta(t) = \frac{2a}{K_a} .$$

For an acceleration in the order of 1×10^{-3} phase cycles/sec^2, the error would be in the order of 5×10^{-3} phase cycle which is about the order of magnitude of accuracy in the overall system. The 0.3 cps bandwidth is therefore limited to the portions of the flight where the phase accelerations are lower than those values. This bandwidth cannot be used during the launch phase since the servo loop would be unable to lock-on or during the first 20 seconds of flight, when the acceleration would be too large; but the 0.3 cps bandwidth could be (and has been) used during the greater portion of the coasting flight with a corresponding improvement in signal to noise ratio and data smoothing.

X-Y Plotter

The X-Y plotter is an ink recorder whose pen rides in the vertical or Y axis on an arm, and the arm travels in the horizontal or X axis. The recorder in the RIT system uses a 10" × 15" sheet of paper on which the real-time azimuth/elevation or the sub-rocket (x-y) coordinates can be plotted. A special graph paper has been used for converting from direction cosines to azimuth/ elevation. The 1x potentiometer outputs of the NS and EW channels drive the arm and pen (or x and y axis) separately. Each potentiometer traverses a 10" length, the diameter of the circle (Figure 13). For a simple check of this transformation, assume for one channel that the direction cosine in the East/West channel is 0 (angle is zero from zenith), and the North/South direction cosine is 1/2. The azimuth should be 0° and the elevation should be 60°. The East/West 1x potentiometer will be at its center point and this will locate the arm at the center point over its 10" travel, the North/South 1x potentiometer will be halfway between the center point and its North horizon point. The 60° elevation circle is located halfway between the zenith and the horizon. The elevation circles were so drawn as to accommodate the conversion between direction cosine and azimuth/elevation.

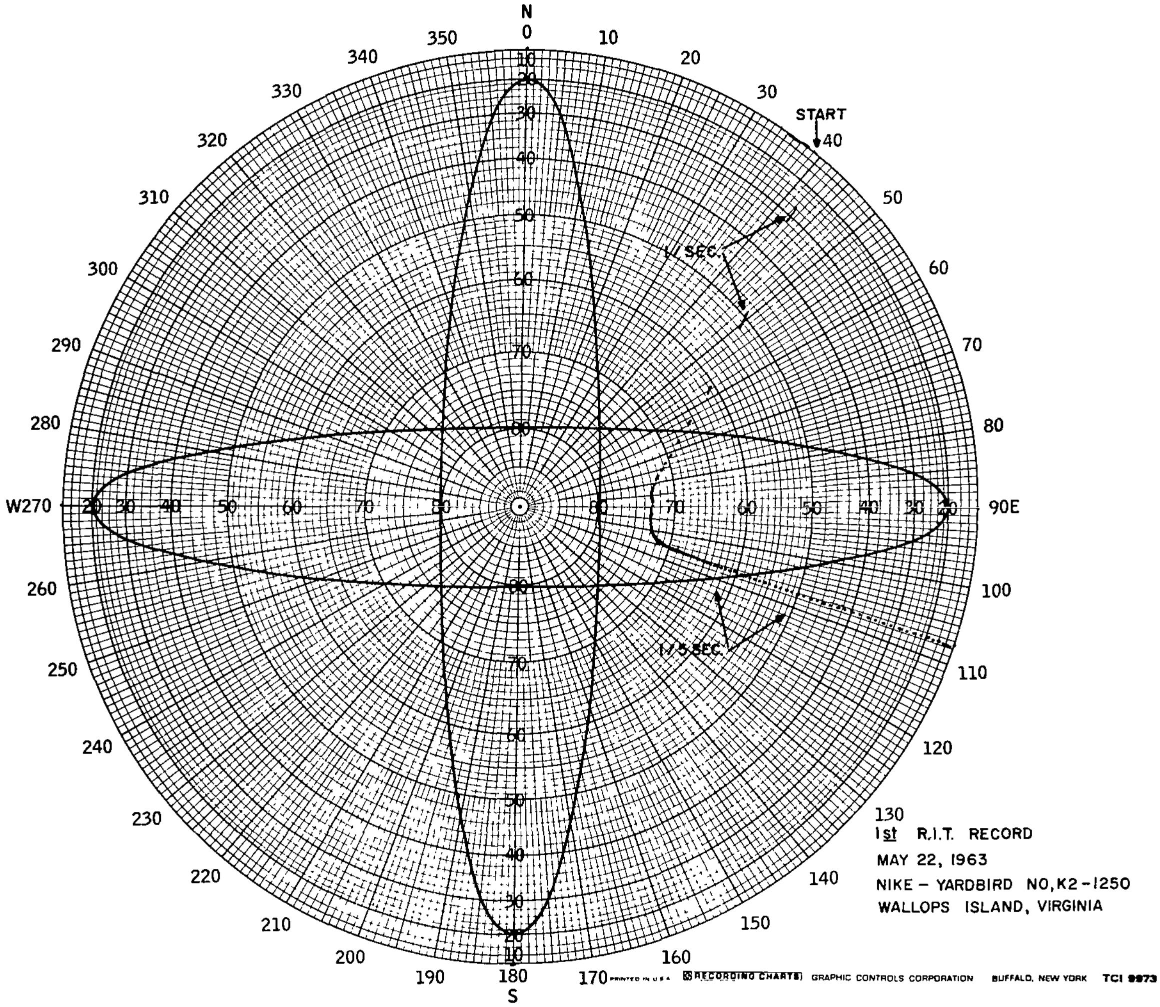


Figure 13—Nike-Yardbird X-Y plot.

Time information can be recorded by lifting the pen at periodic intervals; the decision to record time information is made from the control panel.

Because it is possible to obtain slant range data from a potentiometer in the RADINT system, two very useful real time computations could be plotted. In one case it is possible to compute the sub-rocket position; this would be of use for range safety purposes. Another interesting application would be to compute the real time altitude. This has been done by means of a simple analog computer which essentially performs the following computation:

$$h = R\sqrt{1 - \left(\cos^2 EW + \cos^2 NS\right)}$$

where h is the altitude and R the slant range. The $\cos^2$ functions are readily obtained from the RIT servo system by using a two-gang potentiometer as a servo multiplier.

A plot of real-time altitude is shown in Figure 14. Real time altitude could be useful to program experiments on board the rocket from the ground. This computer is accurate to ±3%; higher accuracies are possible but at increased cost.

Control Panel

The operation of the RIT system is centered at the control panel (see Figures 15, 16). The operator can see the setting of the gear train by either reading the dials on the gear train or by looking at the digital display unit directly above the servo chasis; these both agree. The operator operates the servo gear train from the control panel until each channel is set for the approximate value of the direction cosine from the station to the launcher during the pre-launch operation and this should be within a 1/2 wavelength. The operator can also look at the X-Y recorder and see if the azimuth heading agrees with the known launch azimuth location. The servo unit is placed in a standby mode once the above settings are reached. Both channels are automatically turned on after rocket lift-off. A training delay feature, adjustable from zero launch time to a maximum of 1 second after launch is presently built into the system for those cases where the signal jitters prior to liftoff. The delay could be increased if necessary. Present records at Wallops Island indicate a maximum delay of 1 second is sufficient. If the delay is too great, there is a risk that the servo unit will not lock onto the signal because the phase rate increases rapidly shortly after launch. A delay override switch is provided as a backup

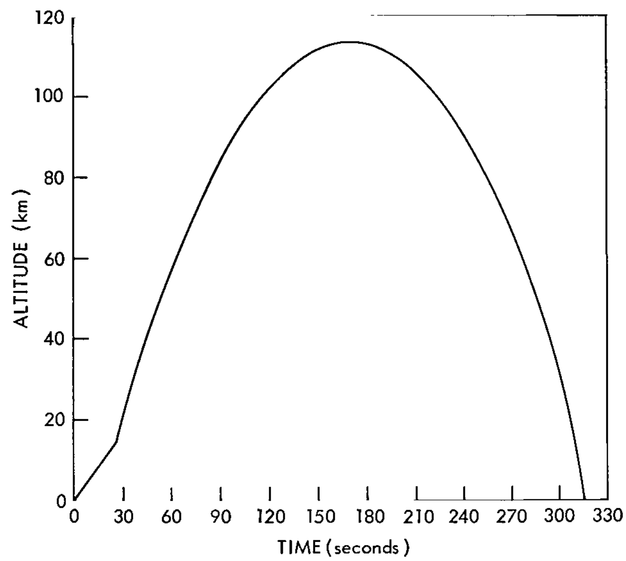


Figure 14–RIT real time altitude plot from Nike Cajun flight, February 3, 1964.

to the automatic switching of the delay unit. The digital system contains the automatic delay tracking feature. The RIT system has been able to track rockets without use of this delay feature, but the orientation of the rocket on the launcher determines the quality of the signal and this cannot be calculated ahead of time. There have been occasions when it was necessary to use this feature.

The RIT system has tracked sounding rockets by locking-on prior to launch. This technique is possible only if the pre-launch phase signal is somewhat phase stable.

A meter for each channel provides a check that the servo tracking filter has locked onto the signal. If the servo unit is tracking properly, the meter will read approximately center scale (zero volts).

Digital System

The purpose of the digital system of the RIT system is to measure automatically and record on punched paper tape the following information: North/South and East/West direction cosines to

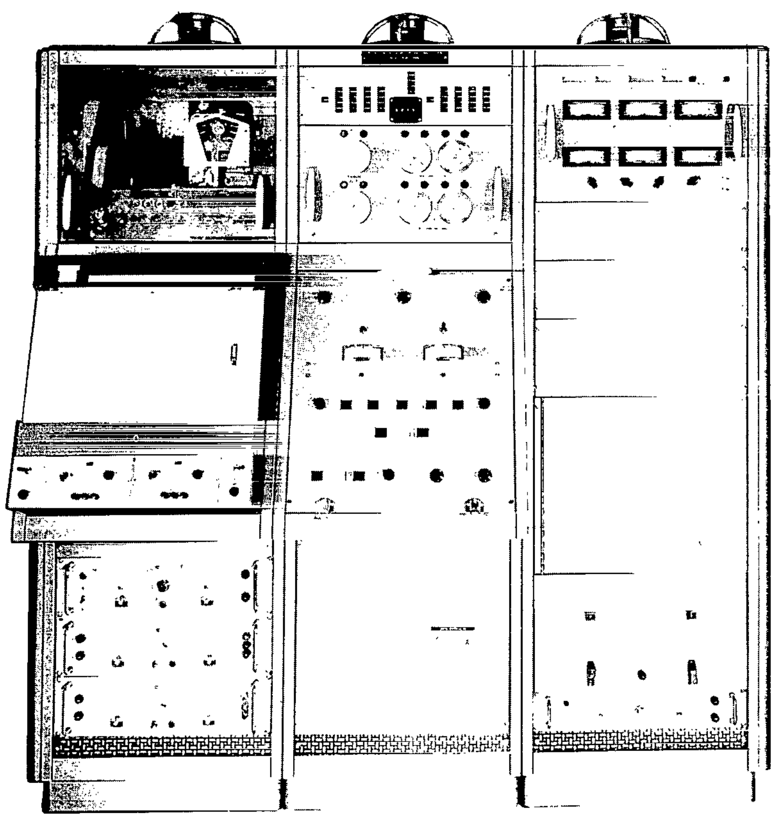


Figure 15—Complete system rack.

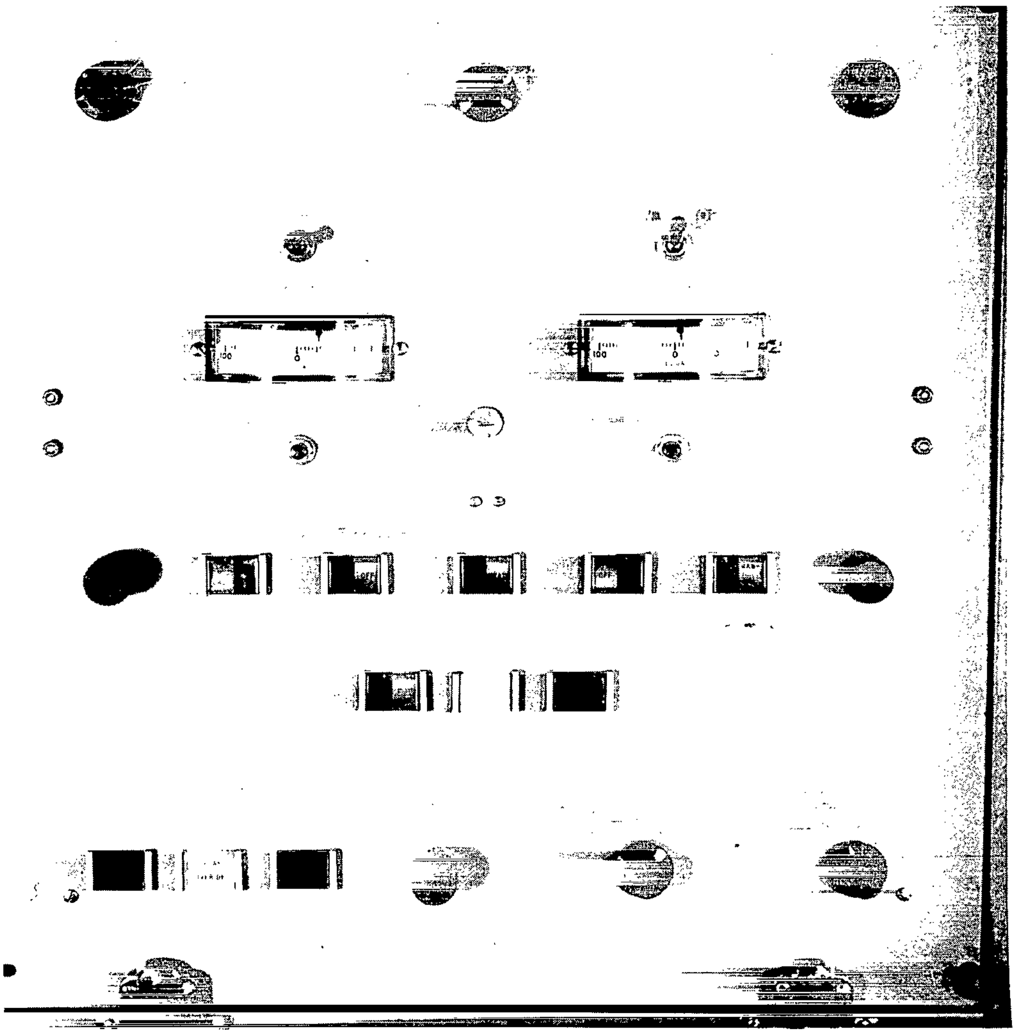


Figure 16—System control panel.

a resolution of .0001 where the direction cosine from horizon to zenith to horizon varies from minus 1 to 0 to plus 1; true rocket slant range whether the rocket is moving toward or away from the station; elapsed time from the moment of rocket launch; receiver AGC level from 1 to 9; and the Tracking Rate Switch position (servo bandwidth selection). After the launch the punched paper tape is fed into a Flexowriter to obtain printed data in tabulated form. The digital system also provides: a Time Light that indicates the moment of rocket launch; a time-coded X-Y pen mode that allows time correlation with the X-Y recorder plot; a signal that automatically starts the Servo System at rocket launch; a 500 cps standard frequency for the RIT Special Local Oscillator; an Error Light that indicates shaft-angle encoder malfunction; and the necessary controls to operate the digital system.

The design of the digital system was dictated by the need to design a reliable, easily maintained system in minimum time to fit in a restricted rack space at reasonable cost. The design philosophy was to build a worst-case-design modulator system, employing off-the-shelf components where possible. The particular digital cards used were worst-case designed and known to be reliable; also, the card specifications were well defined and conservatively rated. The variety of cards available was such that only two special cards had to be designed; the cost of the cards was reasonable in light of the reliability obtained. The digital system has 427 NAND gates (74 cards) consisting of 5 card types; 159 flip-flops (40 cards) consisting of 4 card types; 52 special logic circuits (20 cards) consisting of 8 card types; and 2 specially built cards. Space requirements restricted the maximum number of cards to 140; 136 were actually used. The digital system physically consists of cards and holders; card power supply; card cooling blower; two shaft-angle encoders; Digital Display Unit; high speed paper tape punch and tape winder; power supply for the high speed punch; test panel; and several indicator lights and control switches. The Flexowriter is located externally. Electrically the digital system consists of the shaft encoders and Direction Cosine Translator; Slant Range (Doppler) Counter; Timing and Control Logic (includes Elapsed Time Counter); AGC Unit, Multiplexer; Scanner; Punch Control Unit and Error Light Logic (Figure 17).

Two standard brush-type shaft-angle encoders are used to convert the North/South and East/West shaft-angle information from the Servo System into digital direction cosine information. The encoders have a resolution and accuracy of 1000 counts/revolution with a total of 100 revolutions or 100,000 counts (only 20,000 counts are used for horizon-to-horizon coverage). The encoders use a unit-distance code (to prevent ambiguity errors) consisting of a reflected-decimal code whose decimal characters are represented by a 4-bit reflected-binary code. This code has the following advantages: the conversion to 8421 BCD is relatively easy, the encoder range is easily shifted to obtain a plus and minus range even though an encoder consists of two geared code-discs, and the direction of rotation for an increasing count is easily changed. Upon command the North/South and East/West Direction Cosine Translators read out and store the encoder information. Since the encoders consists of a 100-count coarse disc geared to the 1000-count fine disc, lead-lag techniques are used to prevent ambiguity errors during read out. The encoder data are then converted into 8421 BCD direction cosine information by the Translator logic, whose output has a range from -.9999 to +.9999. The North/South and East/West direction cosines from the Translators are visually displayed by the Digital Display Unit. The Error Light Logic detects and lights an error light if the Translator reads a wrong code from the encoder (usually due to encoder wear).

The Slant Range Counter counts the doppler signal (0 to 4 kc sine wave) furnished by the RADINT receivers which automatically correct rocket roll errors. The counter consists of 7 stages; each stage counts in 8421 BCD either up or down. As the rocket moves away from the station the count increases, and as it approaches the count decreases. A manual switch, thrown at the moment the analog recorders in the RADINT Station indicate a doppler phase reversal, provides the up-down control. The distance between the RADINT Station and the launcher is pre-set into the Slant Range Counter with a Digitswitch so that the count will be correct at all times. At any

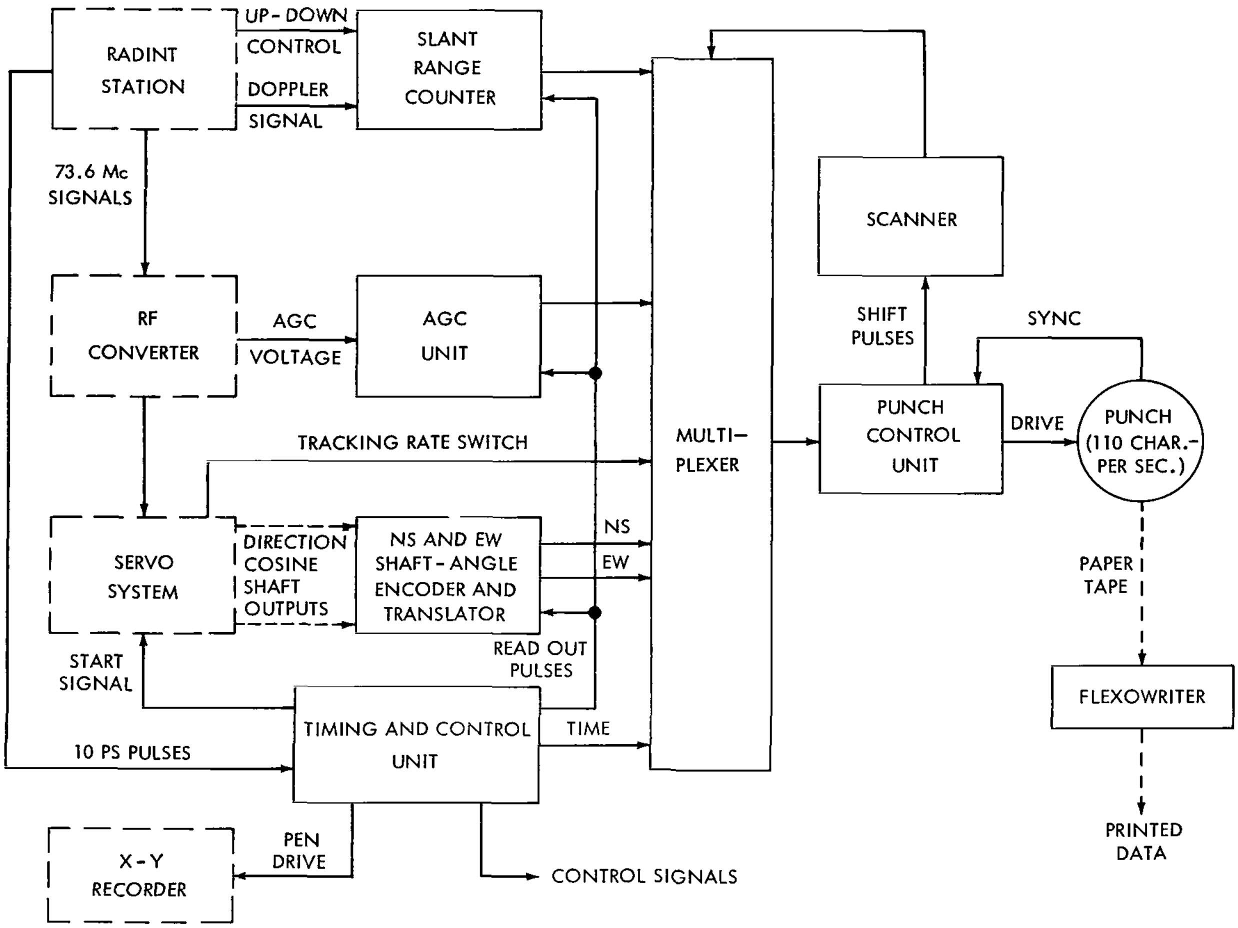


Figure 17—RIT digital system.

arbitrary time, or even simultaneously, the synchronizing circuit for the counter allows a doppler signal to be counted, the up-down control to change, and a counter reading to be dumped into a storage register. The input to the Slant Range Counter has an input impedance of 1 megohm so it will not load down the source.

The receiver AGC voltage is digitized by means of a standard Analog-to-Digital conversion technique. A control gate allows 10 kc pulses to be counted by an 8421 BCD counter, and a Digital-to-Analog card then converts the counter outputs into a staircase analog voltage. A Comparator card closes the control gate when the staircase voltage just exceeds the AGC voltage. The 8421 BCD number left in the counter after the control gate closes is proportional to the AGC voltage level. A weak receiver signal is digitized as a 1 and a strong receiver signal is digitized as a 9. The digitized AGC is visually displayed on the Digital Display Unit. The input to the AGC Unit has an impedance of 1 megohm so the source will not be loaded down.

The Timing and Control Unit performs a number of timing and control functions. One such function is the generation of read-out pulses, which cause the North/South and East/West Direction

Cosine Translators, the Slant Range Counter, and the AGC unit to measure and store data at that time. The Timing and Control Unit is driven by 10pps timing pulses from the RADINT station clock. Before rocket launch the 10 pps timing pulses are turned off. A manual switch resets the elapsed time counter and pre-sets the distance to the launcher into the Slant Range Counter. At rocket launch the 10 pps timing pulses are automatically turned on. The first 10 pps pulse (at $t = 0$ seconds) generates a signal that starts the Servo System and generates a read-out pulse, which causes both the initial Servo System direction cosine setting and the Slant Range Counter pre-set distance to be recorded. Succeeding 10 pps pulses are counted by the elapsed time counter and generate read-out pulses at a rate selectable by a switch. A Time Light circuit indicates when the 10 pps pulses are continuously present and thus indicates the moment of rocket launch. The Timing and Control Unit also continuously generates a 500 cps standard for the receiver Special Local Oscillator and generates a time-coded X-Y pen drive for time correlation with the X-Y recorder plot.

The Multiplexer sequentially samples each BCD character of the data from the North/South and East/West Direction Cosine Translators, the Slant Range Counter, the AGC unit, the Elapsed Time Counter and the Tracking Rate Switch (servo bandwidth). The 8-bit parallel output of the Multiplexer is the standard 8-level code that the Flexowriter uses. The Multiplexer converts the parallel BCD inputs into serial BCD outputs. This 8421 BCD data constitutes the first 4 levels of the output code. The 5th and 6th levels are used for odd parity and the 7th and 8th levels are used in the generation of *carriage return* and *lower case* machine functions. The Multiplexer is sequenced by the Scanner and drives the Punch Control Unit.

The Scanner consists of a simple 26-stage unambiguous, self-starting, self-correcting shift-register counter. A single binary "1", propagated down the shift-register, activates each of the 26 outputs sequentially. When the binary "1" reaches the last stage of the shift-register counter a control flip-flop closes a shift-pulse gate which stops the counter operation. Each time the shift-pulse gate is opened the Scanner sequences through 26 shifts and stops. The shift-register counter is comparable in cost to a counter-decoder type of scanning waveform generator. The shift-register counter has the advantages that the outputs are spike-free, the wiring is easier, and troubleshooting is simpler. Also, the format can be readily changed.

The Punch Control unit uses the information from the Multiplexer to drive a high-speed paper-tape punch at 110 characters per second. The Punch Control unit also converts sync pulses from the punch into shift-pulses for the Scanner; therefore, the Scanner, the Multiplexer and the Punch Control unit are synchronized to the punch. This ensures that data are presented to the punch at the correct times. The punched paper tape is automatically taken up by a winder. Data can be recorded at a rate of one or two data words per second, a data word consisting of 26 characters. This allows either 60 or 30 minutes of recording per roll of paper tape. The tape offers permanent storage, is easily read by eye and can be duplicated by the Flexowriter while simultaneously typing an original and two carbon copies (as is presently done). The Flexowriter is also convenient for adding pertinent identifying information. Should an error occur it will usually be a 1-bit change. This changes the odd parity of that character to even parity. The Flexowriter ignores all even parity codes and this produces an irregularity in the printed format which is easily noticed. The error can later be corrected.

The RIT Digital Unit has a test panel that allows several diagnostic tests to be made without requiring external test equipment. The punch can be tested by itself, the Scanner and the punch can be tested as a unit, or the Scanner can be manually stepped so that the multiplexed information can be punched out character by character. An error light indicates when the encoders make an error or when the test switches are not in the normal operating position.

Special attention has been given to the digital drawings. An effort has been made to make the drawings clear and concise (Figures 18 and 19). Good drawings greatly facilitate system understanding and maintenance. Logic symbols are used that are consistent with the digital card manufacturer's instruction manual.

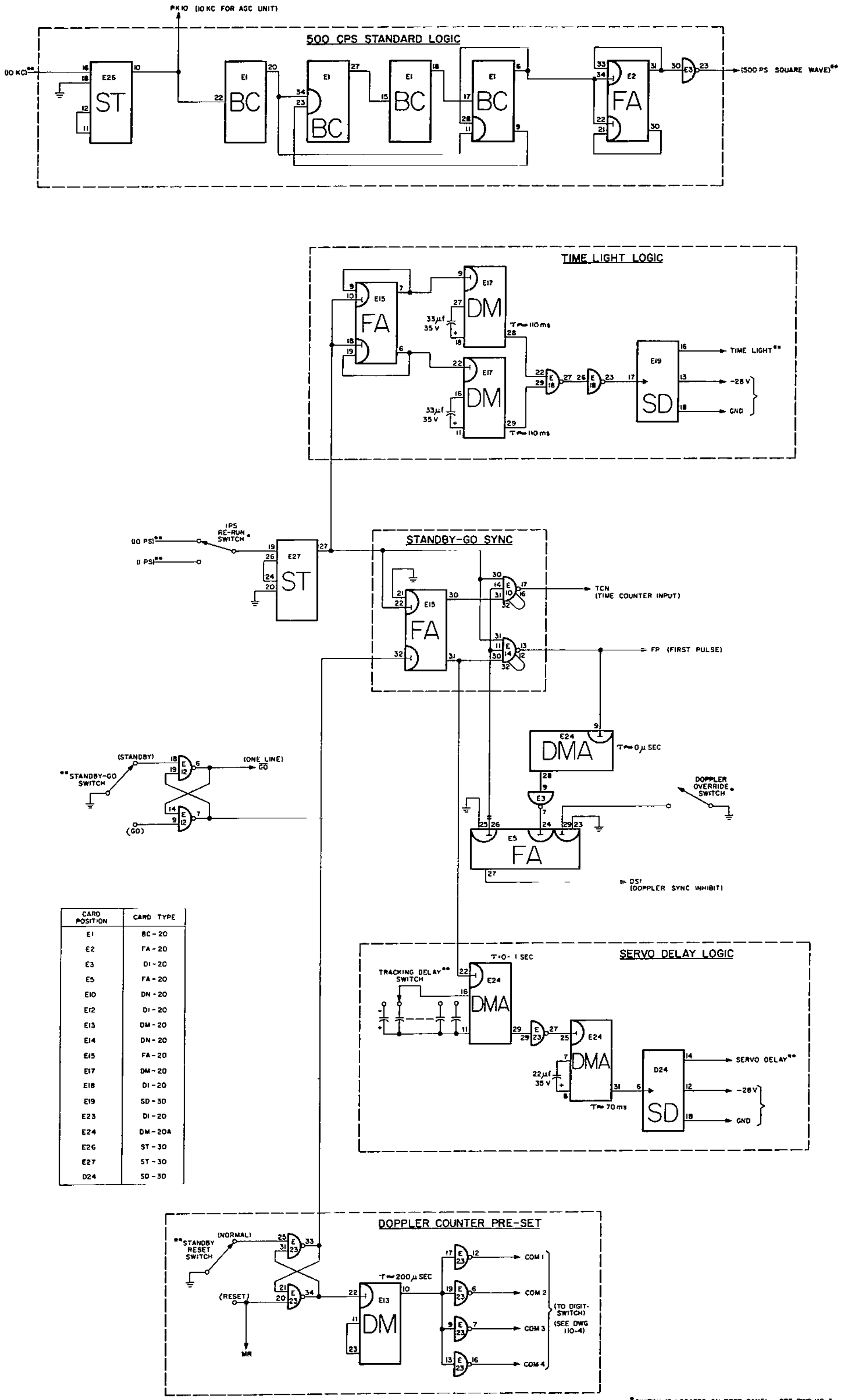
TEST RESULTS

In actual operation between May and December, 1963, the RIT system was able to lock-on and unambiguously track sounding rockets four times, for a 100% record; also the doppler data were very accurate because of the use of a beacon transponder technique. The data from the last two tracks were compared with data from an FPS-16 radar; the deviation in the altitude averaged 9.6 meters at altitudes up to 80 km. Further data were not available as the radar was used to track a balloon ejected from the rocket at 80 km. The slant range was approximately 87 km. Graphical smoothing of the RIT data had very little effect in reducing the average difference between the radar data and the RIT data.

A sample of the digital data recorded on December 7, 1963, for a Nike-Cajun sounding rocket is shown in Figure 20. The first three digits on the left indicate time in seconds from lift-off; the next four digits N/S direction cosine, the next four digits E/W direction cosine (for negative angles and a space for positive angles, where North and East are considered positive directions); next digit is a measure of AGC or signal strength, the number 1 indicating a weak signal and the number 9 a strong signal (the station performs an actual calibration against a known signal strength source); the next digit in this group of two indicates the tracking bandwidth, 0 for the 0.3 cps bandwidth and 1 for the 3 cps bandwidth; the remaining seven digits record slant range data in units dependent on the radio wavelengths, in this case a multiplying factor of 1.0183 converts the data to meters.

The RIT system represents an improvement in resolution by a factor of 3 in measuring phase as compared to the RADINT system. This improvement is not only due to the high resolution of the digital system but also represents the capability of the servo phasemeter.

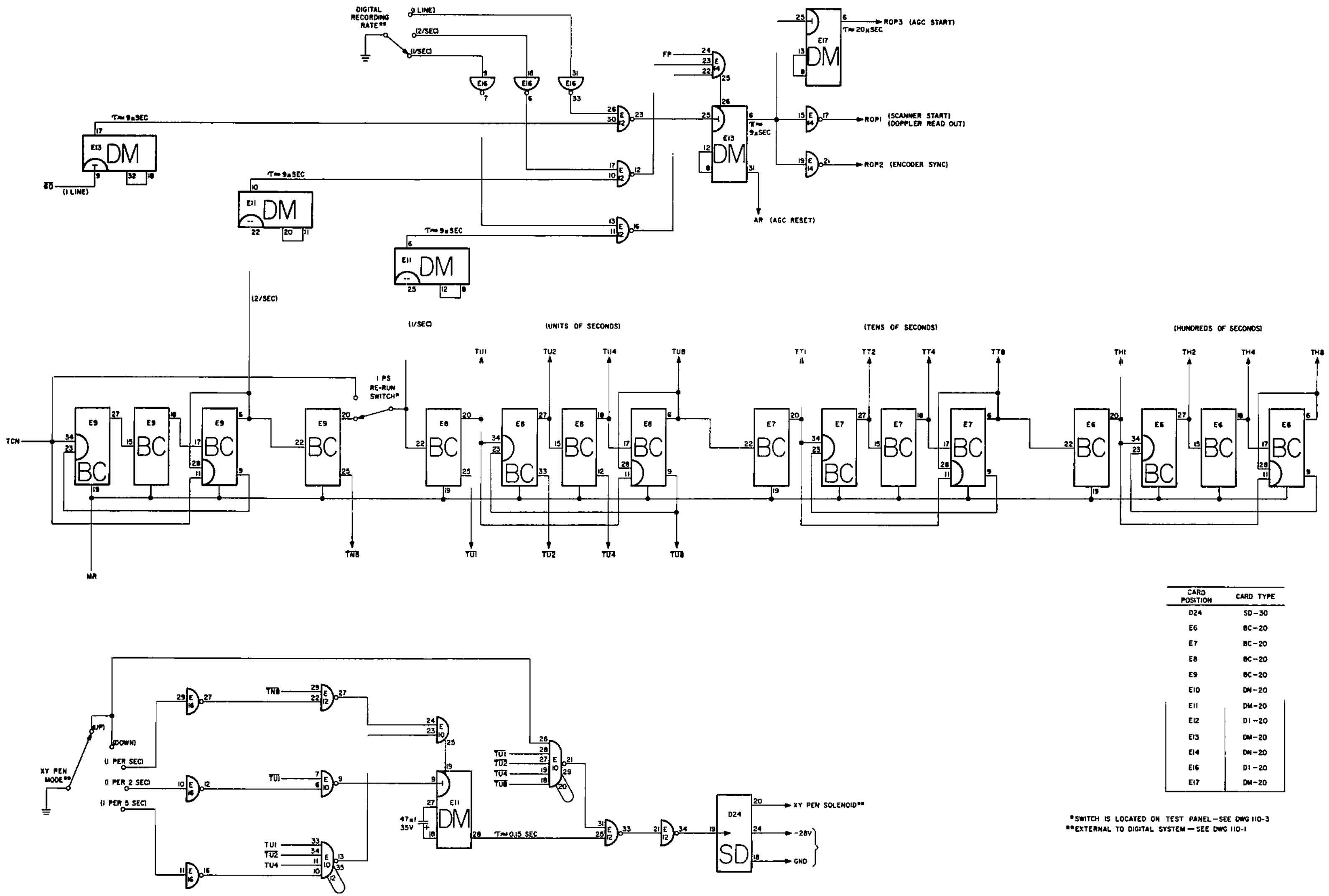
At present the only problem associated with obtaining unambiguous direction cosine data occurs in tracking the rocket from liftoff. There have been occasions when the signal at liftoff had a large amount of phase jitter in which the servo system locked onto the incorrect lobe. This means that the



CARD POSITION	CARD TYPE
E1	BC-20
E2	FA-20
E3	DI-20
E5	FA-20
E10	DN-20
E12	DI-20
E13	DM-20
E14	DN-20
E15	FA-20
E17	DM-20
E18	DI-20
E19	SD-30
E23	DI-20
E24	DM-20A
E26	ST-30
E27	ST-30
D24	SD-30

*SWITCH IS LOCATED ON TEST PANEL—SEE DWG 110-3
**EXTERNAL TO DIGITAL SYSTEM—SEE DWG 110-1

Figure 18—Timing control digital system.



CARD POSITION	CARD TYPE
D24	SD-30
E6	BC-20
E7	BC-20
E8	BC-20
E9	BC-20
E10	DN-20
E11	DM-20
E12	DI-20
E13	DM-20
E14	DN-20
E16	DI-20
E17	DM-20

*SWITCH IS LOCATED ON TEST PANEL—SEE DWG 110-3
**EXTERNAL TO DIGITAL SYSTEM—SEE DWG 110-1

Figure 19—Timing logic digital system.

data in that channel are shifted by .0625N, N being the number of lobes shifted. Since this is a relatively easy mathematical manipulation, the data obtained are still quite useful after the shift has been performed. The analog record is necessary for this reason, i.e., to confirm proper operation of the servo unit. It is also possible to position an antenna automatically with the RIT System. A computer which would convert direction cosine data to X-Y data is being developed for other uses, and could be used in this case. This would allow use of a high gain telemetry antenna.

030-0123	3013	81	0027225
030-0137	3011	81	0027902
031-0150	3011	71	0028573
031-0162	3013	81	0029239
032-0173	3017	71	0029901
032-0183	3018	81	0030559
033-0194	3017	71	0031213
033-0204	3019	81	0031863
034-0213	3024	71	0032509
034-0222	3023	71	0033152
035-0231	3025	71	0033791
035-0238	3030	71	0034428
036-0247	3029	71	0035060
036-0254	3035	71	0035690
037-0259	3042	70	0036317
037-0266	3044	70	0036941
038-0272	3044	70	0037562
038-0279	3046	70	0038180
039-0286	3047	70	0038794
039-0293	3050	70	0039406
040-0300	3054	70	0040016

Figure 20—Digital record hard copy; (portion) of RIT digital record of December 7, 1963 Nike Cajun firing.

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NASA-Langley, 1965

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